# Estimation of Soil Moisture with the combined L-band Radar and Radiometer Measurements


Jiancheng Shi
ICESS
University of California,
Santa Barbara, CA 93106, USA,
shi@icess.ucsb.edu

Y. Kim, J. J. Van Zyl, and E. Njoku,
NASA JPL, Pasadena,
CA 91109 USA

T. Jackson
USDA ARS
Beltsville,
MD, 20705 USA

K. S. Chen
CSRSR
National Central University,
Chung-Li, Taiwan

P.O'Neill
NASA GSFC Greenbelt,
MD 20771, USA



**Abstract – This study demonstrates a technique of estimating soil moisture using the combined passive/active L-band microwave measurements. It shows 1) evaluation of the small albedo assumption for using dual polarization passive measurements, 2) development of a synthesized technique to estimate soil moisture, and 3) evaluation with ground soil moisture measurements from the SMEX02 experiment data.**


## I. INTRODUCTION

Soil moisture is a key parameter in numerous environmental studies, including hydrology, meteorology, and agriculture. It plays an important role in the interactions between the land surface and the atmosphere, as well as the partitioning of precipitation into runoff and ground water storage. Therefore, the spatial and temporal dynamics of soil moisture are important parameters for various processes in the soil-vegetation-atmosphere-interface. The Hydrosphere State Mission (Hydros) with both Active/Passive L-band instruments has been approved by NASA for monitoring global soil moisture and freeze/thraw. The Hydros instrument combines radar and radiometer subsystems. The radar operates with VV, HH, and HV transmit-receive polarizations, and uses separate transmit frequencies for the H (1.26 GHz) and V (1.29 GHz) polarizations. The radiometer operates with V, H and U (third Stokes parameter) polarizations at 1.41 GHz.

In attempt to use the active or passive microwave remote sensors for estimation of soil moisture, we are mainly facing two common problems: effects of surface roughness and vegetation cover. Natural variability and the complexity of the vegetation canopy and surface roughness significantly affect the sensitivity of backscattering and brightness temperature to soil moisture. Backscattering and brightness temperature signals from the vegetated areas is a function of water content and its spatial distribution as determined by vegetation structure and underlying surface conditions including surface roughness parameters and dielectric properties. Due to the limited observations from either passive or active measurements alone, an ill condition, the number of measurements and equations are less than the number of unknowns, is expected. It results in the uncertainties in estimation of soil moisture.

In this study, we study a combined active/passive technique to estimate surface soil moisture with the focus on the short vegetated surfaces. We first simulated a database for both active and passive signals under Hydros's sensor configurations using the radiative transfer model with a wide range of conditions for surface soil moisture, roughness and vegetation properties that we considered as the random orientated cylinders. Using this database, we developed 1) the techniques to estimate surface soil moisture. We will demonstrate this technique with the model simulated data and its validation with the airborne PALS image data from the soil moisture SMEX'02 experimental data.

## II. INVERSION MODEL DESCRIPTION

The simulation models used in this study are based on the commonly used three components emission and backscattering model concept with no consideration on the polarization dependence of the vegetation extinction properties. They are given as

$$\begin{aligned} T_{Bp}^{t} &= T^{v} \cdot (E_{p}^{v} + E_{p}^{sv}) + T^{s} \cdot E_{p}^{s} \cdot L_{p} \\ \sigma_{pq}^{t} &= \sigma_{pq}^{v} + \sigma_{pq}^{sv} + \sigma_{pq}^{s} \cdot L_{pq}^{2} \end{aligned} \tag{1}$$

The superscrip *t, v, s*, and *sv* indicate the total and components from vegetation, soil, and soil-vegetation interaction terms, respectively. $T^v$ is the temperature of vegetation and $T^s$ is the soil temperature. $E_p^v=(1-\omega)(1-L_p)$ is the emissivity of the vegetation layer. $E_p^{sv}= E_p^v R_p^e L_p$ is the emissivity due to vegetation-surface interaction. $L_p=exp(-\tau_p/cos\theta)$ is the one way attenuation factor or transmittivity of vegetation layer. The τ is

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**25 JUL 2005** | 2. REPORT TYPE<br>**N/A** | 3. DATES COVERED<br>**-** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Estimation of Soil Moisture with the combined L-band Radar and Radiometer Measurements** | 5a. CONTRACT NUMBER<br>5b. GRANT NUMBER<br>5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER<br>5e. TASK NUMBER<br>5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**ICESS University of California, Santa Barbara, CA 93106, USA** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**See also ADM001850, 2005 IEEE International Geoscience and Remote Sensing Symposium Proceedings (25th) (IGARSS 2005) Held in Seoul, Korea on 25-29 July 2005.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | |
| **unclassified** | **unclassified** | **unclassified** | **UU** | **4** | |

the optical thickness. The direct volume backscattering component is given by

$$\sigma_{pq}^{v}(\theta) = 0.5\kappa_{s}^{pq}\left(1 - L_{pq}^{2}\right)/\kappa_{e}^{pq} \tag{2}$$

The surface emission and backscattering are simulated by the Advanced Integral Equation Model [1-2].

## III. EVALUATION OF SMALL ALBEDO ASSUMPTI ON IN PASSIVE MEASUREMENTS

For convenience of analyses, we re-write (1) for passive emissivity as

$$\begin{aligned} E_{p}^{t} &= 1 - \omega\cdot(1 - L_{p}) - R_{p}^{e}\cdot L_{p}\cdot\left[1 - E_{p}^{v}\right] \\ &= 1 - V_{c} - R_{p}^{e}\cdot V_{e} \end{aligned} \tag{3}$$

Where $V_{c} = \omega\cdot(1 - L_{p})$ is the vegetation correction factor. $V_{e} = L_{p}\cdot(1 - E_{p}^{v})$ is the vegetation attenuation factor. Due to Vc typically quite small, the study showed that the effect of Vc wss small on estimation of soil moisture when using H polarization and was assumed that ω=0 [3]. This is because 1) the vegetation effects in low frequency passive signals are mainly dominant by the absorption and 2) the surface effective reflectivity in H polarization has much larger impact on the measured emission signals than that from the scattering generated signals. With the small albedo assumption of ω=0, (3) becomes

$$E_{p}^{t} \approx 1 - R_{p}^{e}\cdot L_{p}^{2} \tag{4}$$

To evaluate this approach on estimating soil moisture for using the dual polarization measurements, we simulated the emission signals using (3) with the τ: 0.01 to 0.6, ω: 0.01 to 0.05 and a wide range surface soil moisture and roughness conditions. **Figure 1** (left) shows the histogram of $V_c$ from this simulation. It can be seen that $V_c$ are quite small with a range less than 0.03. In order to examine its impact on the description of the relationship between V and H polarizations, we compared

$$\frac{1 - V_{c} - E_{v}^{t}}{1 - V_{c} - E_{h}^{t}} \approx \frac{R_{v}^{e}\cdot V_{e}}{R_{h}^{e}\cdot V_{e}} = \frac{R_{v}^{e}}{R_{h}^{e}} \tag{5}$$

**Figure 1** (right) shows the left side of (5) as x-axis that represents the case without getting ω=0 and the right side of (5) as y-axis that represents the effective reflectivity ratio value with assumption of ω=0. It shows that the small albedo assumption will result in the significant effects on deriving the ratio of the surface polarization reflectivity, which will greatly impact on the estimation of soil moisture. This is because the emissivity of V polarization can be quite close to unity so that Vc can be at the same magnitude as the effective reflectivity. Therefore, the effect of Vc has to be take into account in estimation of soil moisture when using the ratio approach.

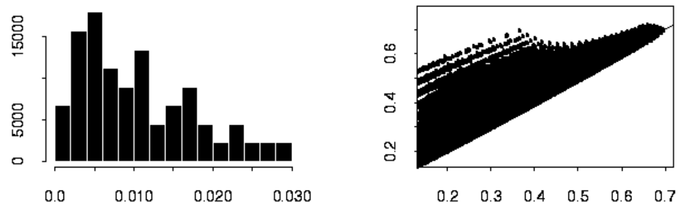



**Fig. 1.** The histogram of the simulated $V_c$ at left and the comparison on the polarization ratio signals with (right side of (4)) and without (left side of (4)) the small albedo assumption.

## IV. ESTIMATION OF THE VEGETATION CORRECTION FACTOR $V_c$ WITH ACTIVE RADAR MEASUREMENTS

Natural variability and the complexity of the vegetation canopy and surface roughness significantly affect the sensitivity of radar backscattering to soil moisture. Backscattering signals from vegetated areas is a function of water content and its spatial distribution as determined by vegetation structure and underlying surface conditions. It has been realized that the different radar polarization measurements has the different sensitivities to the different surface properties. Especially, the radar cross-polarization measurements are very sensitive to the vegetation information since the surface backscattering does not generate significant cross-polarization signal. As shown in [4], the direct volume backscattering component of the co-polarizations in (1) for the random orientated short cylinders can be directly estimated from the cross-polarization signals. That is

$$\sigma_{pp}^{v} = 3\cdot\sigma_{vh}^{t} \tag{6}$$

In comparison of $V_c$ and $\sigma_{pp}^{v}$, it can be found that they are highly correlated. Their relationship can be well characterized as

$$\log(V_{c}) = a + b\cdot\log(\sigma_{pp}^{v}) \tag{7}$$

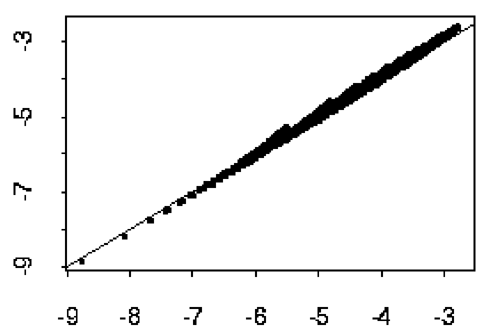



**Fig. 2**. Comparison of of $V_c$ of the simulated by (3) (x-axis) and the estimated from the direct volume backscattering component (y-axis).

**Figure 2** shows the comparison of $V_c$ of the simulated data using (3) and the estimated from the direct volume backscattering component of the simulated radar signals using (7). It demonstrated that $V_c$ could be estimated from radar cross-polarized backscattering measurements by using (6) and (7). It improves the accuracy in describing the relationship between V and H polarization signals in the soil moisture retrieval by the passive measurements.

## V. A SYNTHESIZED INVERSION TECHNIQUE TO ESTIMATE SOIL MOISTURE USING PASSIVE MEASUREMENTS

With the estimated $V_c$ parameter from radar, we can now obtain the measurements

$$1 - V_c - E_p^t = R_p^e \cdot V_e \tag{8}$$

For estimation of soil moisture, we derived a synthesized technique that consists the three formulas with the different sensitivity to the different surface properties.

The first formula is the polarization ratio to derive the effective reflectivity ratio measurements.

$$\frac{R_v^e \cdot V_e}{R_h^e \cdot V_e} = \frac{R_v^e}{R_h^e} = \frac{r_v \cdot H_v}{rh \cdot H_h} \tag{9}$$

where $H_p$ represents the effect of the surface roughness at polarization p. Since it is assumed that there is no polarization dependence for the vegetation extinction properties in this study, the ratio measurement will cancel out the vegetation attenuation effect – $V_e$. This measurement provides the information on the soil moisture and roughness. It is insensitive to vegetation properties.

The second formula is obtained from our bare surface soil moisture retrieval study [4]. For bare surface, the Fresnel reflectivity ratio can be estimated by

$$\frac{r_v}{r_h} = \exp\left[a + b \cdot \log(R_v^e) + c \cdot \log(R_h^e) + d \cdot R_v^e / R_h^e\right] \tag{10}$$

The parameters a, b and c are determined through regression analyses from our AIEM model simulated database. These parameters are dependent only on incidence angle. This model uses the different weight on the surface effective reflectivity measurements at different polarizations to minimize the surface roughness effects so that the response of the measurements to the Fresnel reflectivity ratio (left side of (10)) can be estimated. Under present of the vegetation, it becomes

$$\frac{r_v}{r_h} \cdot V_e^{b+c} = \exp\left[a + b \cdot \log(R_v^e \cdot V_e) + c \cdot \log(R_h^e \cdot V_e) + d \cdot R_v^e / R_h^e\right] \tag{11}$$

This measurement provides the information on the soil moisture and the vegetation attenuation. It is insensitive to surface roughness properties.

The third formula is obtained based on the relationship between the Fresnel reflectivity at V and H polarizations. It can be well described as

$$r_v = r_h^a \tag{12}$$

which leads to

$$\frac{R_v^e \cdot V_e}{(R_h^e \cdot V_e)^a} = \frac{H_v}{H_h^a} \cdot V_e^{1-a} \tag{13}$$

from (8) . This measurement provides the information on the surface roughness and the vegetation attenuation. It is insensitive to soil dielectric properties.

However, the roughness presentation in (13) does not directly related to the roughness presentation in (9). In order to estimate soil moisture, we need to characterize the relationship between the roughness parameters in (9) and (13). **Figure 3** (left) shows the relationship between $H_v/H_h$ as x-axis and $H_v/H_h^a$ as y-axis in our AIEM model simulated database. It shows that these two roughness properties have a fairly good relation. By adding the effective reflectivity ratio measurements, their relationship can be well described as

$$\frac{H_v}{H_h^a} = f + g * \frac{H_v}{H_h} + h * \frac{R_v^e}{R_h^e} \tag{14}$$

where *f, g*, and *h* are coefficients determined from the regression analyses. **Figure 3** (right) shows the comparison between the left side and right side of (14).

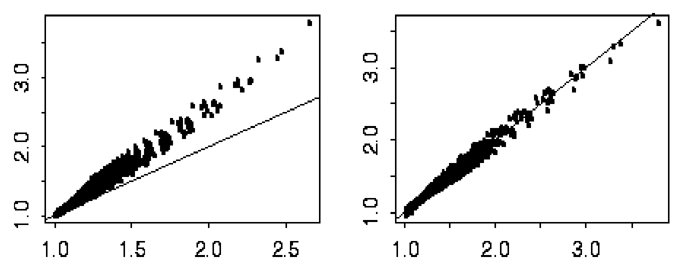



**Fig. 3.** The relationship between $H_v/H_h$ as x-axis and $H_v/H_h^a$ as y-axis (left) and the comparison between the left side and right side of (14).

With above formulas (8) to (14), we are now able to estimate the Fresnel reflectivity ratio, the surface roughness ratio, and the vegetation attenuation factor. We first use the radar cross-polarization measurement with (6) and (7) to estimate the vegetation correction factor $V_c$. Then, we loop through the possible vegetation attenuation factor $V_e$ and select the minimum error from examining (9), (11), (13), and (14) to find the estimations. After we obtain the estimation of the Fresnel reflectivity ratio, it can be converted to soil moisture.

**Figure 4** shows the histogram of the absolute errors on estimation of soil moisture from the performance of the above technique using our simulated emission database. This database covers a wide range of vegetation extinction properties and surface dielectric and roughness properties with total 240,000 simulated data. The RMSE of the estimated soil moisture is 0.03 or 3 % for volumetric soil moisture.

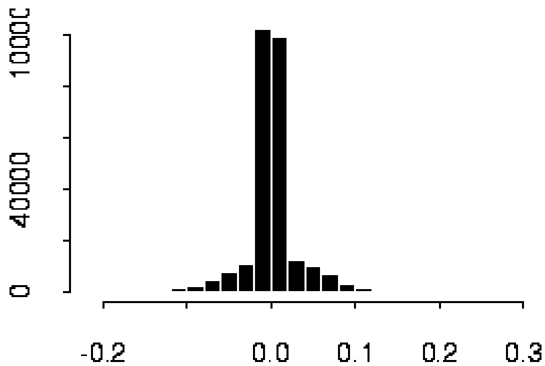



**Fig. 4.** The histogram of the absolute soil moisture errors.

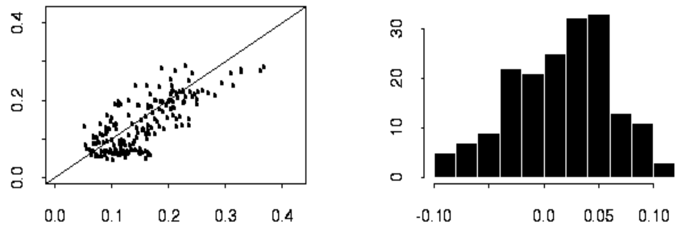
## VI. EVALUATION WITH PALS MEASUREMENTS

PALS is a non-scanning real aperture combined microwave radiometer and radar, operating at 1.41 and 2.69 GHz (radiometer) and 1.26 and 3.15 GHz (radar) with multiple polarizations. The instrument was designed for high accuracy measurements of ocean salinity and soil moisture. The radiometer operates at V (vertical) and H (horizontal) polarizations, while the radar operates at VV, HH, and VH polarizations. For SMEX02 this angle was fixed at 45°. The instrument thus samples a single footprint track along the flight path. At a nominal flight altitude of 1 km and incidence angle of 45° the instantaneous 3-dB footprints at the surface are approximately 330 x 470 m. Additional details of the instrument design and engineering data are provided in [4].

PALS flew several flight lines each day over the test area from June 25 to July 8, 2002. During the late June, the soil was very dry. At early July, there were several rainstorms moved through the area providing an opportunity to observe a large dynamic soil moisture range. Vegetation types in the test area are mainly corn and soybean with the field-averaged vegetation water contents observed on the ground primarily within the a few kg $m^{-2}$ range during the SMEX02 experiment. The ground soil moisture at different soil depth was sampled over 32 field test sites intensively during the experiment. There are total of 182 soil moisture data available with the corresponding PALS measurements from 6 different days.

**Figure 5** (left) shows the comparison between the averaged volumetric soil moisture from the ground measurements and that estimated using L-band PALS measurements by the technique described in last section. In overall, the estimated soil moisture matches the trend of that measured on the ground and with a reasonable accuracy. The accuracy in terms of RMSE is 0.047 or 4.7 % of the volumetric soil moisture. **Figure 5** (right) shows the histogram of the absolute errors of the estimated volumetric soil moisture. As we can see that there is a system error or bias in the estimation. The largest error can reach 10 %. Through our analyses, it was found that the estimation for the soybean fields had a better accuracy than that from the corn fields. This may be resulted from our assumption on the no polarization dependence of vegetation cover in our inversion technique. However, corn has a strong preferred special structure and orientation. It results in a significant polarization dependence in the extinction properties of the vegetation, which has a great impact on soil moisture estimation.

**Fig. 5.** (left) Comparison of the estimated soil moisture from the ground *in-situ* measurements (x-axis) and that estimated from the PALS L-band




measurements (y-axis). (right) The histogram of the absolute errors of the estimated volumetric soil moisture.

## VII. SUMMARY

In this study, we develop a combined active/passive technique to estimate surface soil moisture with the focus on the short vegetated surfaces. It shows that the small albedo assumption will result in the significant effects on deriving the ratio of the surface polarization reflectivity, which will greatly impact on the estimation of soil moisture. We developed a technique to estimate soil moisture, which includes the estimation of the vegetation parameter of $V_c$ using the cross-polarization measurements of radar, a synthesized measurements from radiometer. The test from the SMEX02 PALS measurements performed reasonable well with the RMSE of 4.7 % for volumetric soil moisture estimation. It is also found the polarization dependence of the vegetation cover has a great impact on the soil moisture estimation and needs to be considered in future study.

## REFERENCES

[1] Wu, T. D., K. S. Chen, J. Shi and A. K. Fung, “A Transition Model for the Reflection Coefficient in Surface Scattering”, IEEE Transactions on Geoscience and Remote Sensing, Vol. 39, No. 9, pp. 2040-2050, Sept., 2001.

[2] Chen, K. S., T. D. Wu, L. Tsang, Qin Li, J. Shi and A. K. Fung, “The Emission of Rough Surfaces Calculated by the Integral Equation Method with a Comparison to a Three-Dimensional Moment Method Simulations”, IEEE Transactions on Geoscience and Remote Sensing, 41(1):90-101, Jan. 2003.

[3] Jackson, T. J. and D. M. Le Vine, “Mapping surface soil moisture using an aircraft-based passive microwave instrument: algorithm and example,” *J. Hydrology*, vol. 184, pp. 85-99, 1996.

[4] Freeman, A. and S. L. Durden, “A three-component scattering model for polarimetric SAR data”, *IEEE Trans. Geosci. and Remote Sens.*, 36(3):963-973, May 1998.

[5] Wilson, W. J., S. H. Yueh, S. J. Dinardo, S. Chazanoff, F. K. Li, and Y. Rahmat-Samii, “Passive Active L- and S-band (PALS) microwave sensor for ocean salinity and soil moisture measurements,” *IEEE Trans. Geosci. Rem. Sens.*, vol. 39, pp. 1039–1048, 2001.